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Influential aspects of glacial resource for establishing Kuhl system (gravity flow irrigation) in the Hindu Kush, Karakoram and Himalaya ranges

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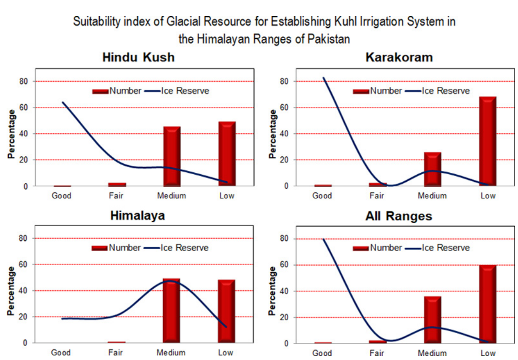
HIGHLIGHTS

- Kuhl irrigation system is highly effective in supplying snow and glacial melt water for agricultural development in the Himalayan region.
- Suitability indexing approach based on glacier accessibility and yield was adopted to assess kuhl irrigation potential in the Himalayan ranges.
- Suitability index was found good for about 1.4% HKH glaciers constituting 80% ice reserves and low for 60% glaciers with 1.5% ice reserves only.
- Unit glacial reserve was found maximum for Shigar basin, i.e., about 1.44 km^3, and among HKH ranges, for the Karakoram, i.e., about 0.46 km^3.

GRAPHICAL ABSTRACT



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ABSTRACT

The meltwater components play an important role in the hydrological regime of the Hindu Kush, Karakorum and Himalaya (HKH) region, in terms of high demand of water for food and fiber from snow and glacial resource. The communities of Himalayan mountains are facing challenges of food security owing to lack of the resource information for meeting their water requirements. In this study, suitability index approach was adopted to assess glacier resource potential for establishing kuhl irrigation system in HKH ranges of Pakistan. The basis of indexing is glacier accessibility and water yield potential of the glacial resource for irrigation estimated in terms of number and ice reserve of the glaciers. The suitability index was found good for about 1.4% glaciers constituting about 80% of the total ice reserves of the HKH region. Medium suitability constitutes about 36.1% glaciers with 12.6% of the total ice reserves, while low suitability was assessed for about 60% glaciers containing 1.5% ice reserves only. Maximum unit glacial reserve was estimated for Shigar basin, i.e., 1.44 km^3, and among HKH ranges, 0.46 km^3 for the Karakoram range. A regular monitoring of the glacial resource would prove helpful in assessing vulnerability of this resource to climate change in the high Himalayan region in future.

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1. Introduction

The water tower characteristics of the Karakoram-Himalaya Ranges of Asia has gain interest of global research communities owing to the snow and glacial sensitivity to climate change (Immerzeel et al., 2010; Archer et al., 2010; Bocchiola et al., 2011; Bajracharya et al., 2015). The human-water interaction in various parts of the Upper Indus basin (e.g. Kreutzmann, 2000, 2011, 2012; Parveen et al., 2015; Nüsser and Schmidt, 2016) and in Ladakh, Kashmir (Labbal, 2000; Dame and Nüsser, 2011; Nüsser et al., 2012) has been studied by many researchers as getting insight of the inhabitant dependence on water resource of the complex hydroglacial environment for their sustenance. The scope of boring tube wells and canals is limited to the low lying areas, whereas methods based on rain (like roof water harvesting and rain water harvesting) are usually preferable in the monsoon belt of the Indus basin. Therefore, kuhl irrigation system is mostly practiced in the Himalayan region, through diverting snow/glacial melt water for increasing crop productivity. Beside irrigation, kuhls are also supplying water for domestic use, meet livestock needs and in cases deliver water to small-scale hydropower units (SDPI, 2002). In contrast to highly variable flows of rainfed streams, there exist a least year-to-year variability in glacier-fed kuhl irrigation system (Vender Velde, 1989). Monitoring of the high altitude cryosphere of HKH region has now been possible through efficient use of remote sensing technique coupled with ground observations (Ashraf et al., 2015).

In the present study, indexing approach was adopted to assess glacier resource potential for establishing kuhl irrigation system in the Himalayan mountain ranges of Pakistan. The basis of indexing is glacier accessibility and water yield potential of the glacial resource for irrigation estimated in terms of number and ice reserve of the glaciers.

2. Glacial environment of the study region

The study area stretches over 0.13 million km^2 in the glaciated Hindu Kush, Karakorum and Himalaya (HKH) region of Pakistan (Fig. 1). It is a junction of three great Himalayan ranges, i.e., Hindu Kush, Karakoram and Himalayas, the snow and glaciers resources of which contribute >50% runoff to the Indus river system in Pakistan (Winiger et al., 2005). The elevation ranges from 366 m in the southwest to over 8600 m towards northeast (Fig. 2). Due to rugged topography, temperate climate and partial monsoon effect, the region possesses numerous small and large glaciers and associated glacial lakes. The glaciers of whole Indus basin lie within 2400–8600 m elevation range – about 59% within 4800–5800 m elevation range (ICIMOD, 2011). The distribution of glaciers varies with location and climatic conditions, e.g. the snouts of some large sized glaciers extend down below 2700 m elevation in the semi-arid valleys (Roohi et al., 2005).

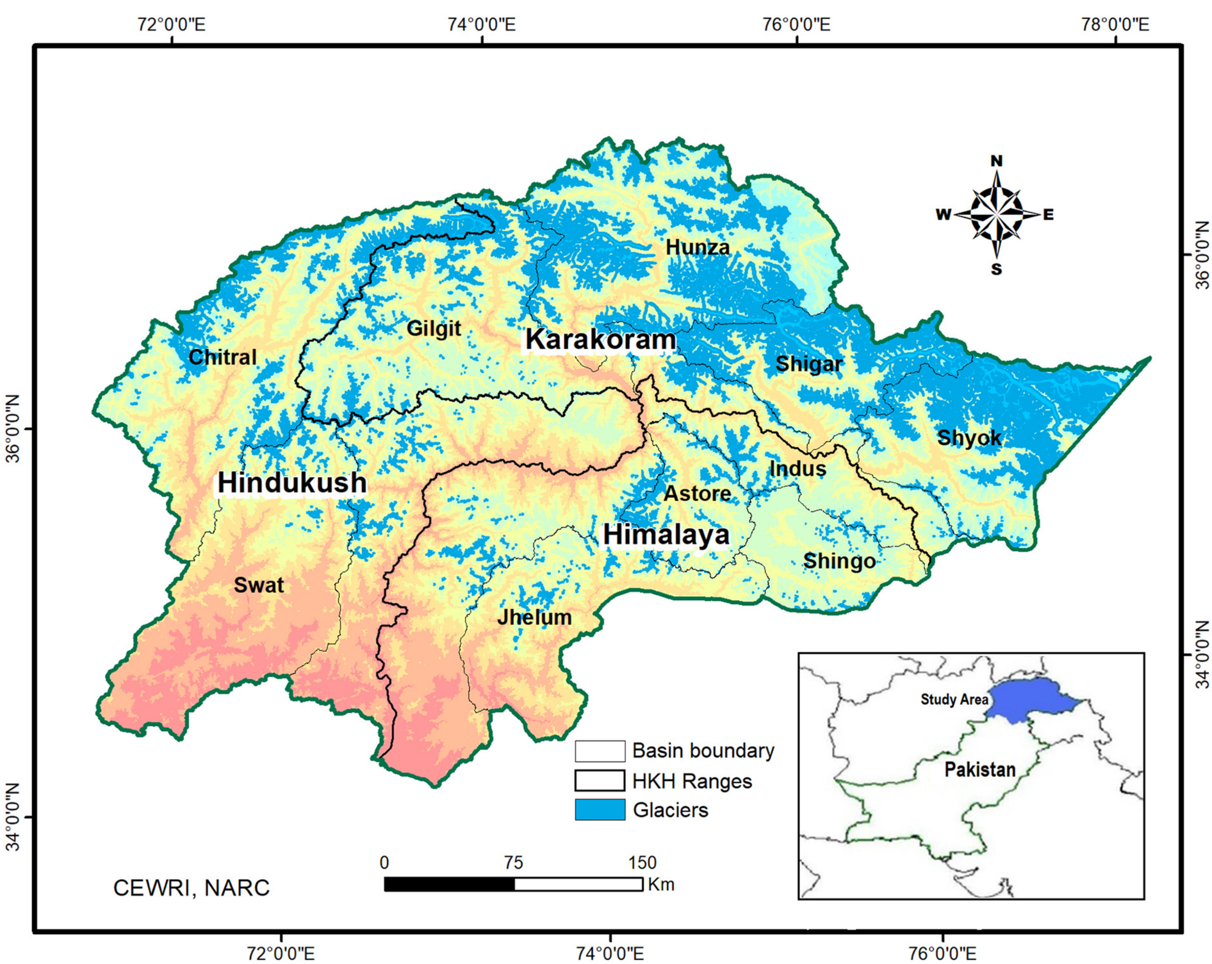

Fig. 1. Geographic setting of the three Himalayan Ranges in Pakistan.

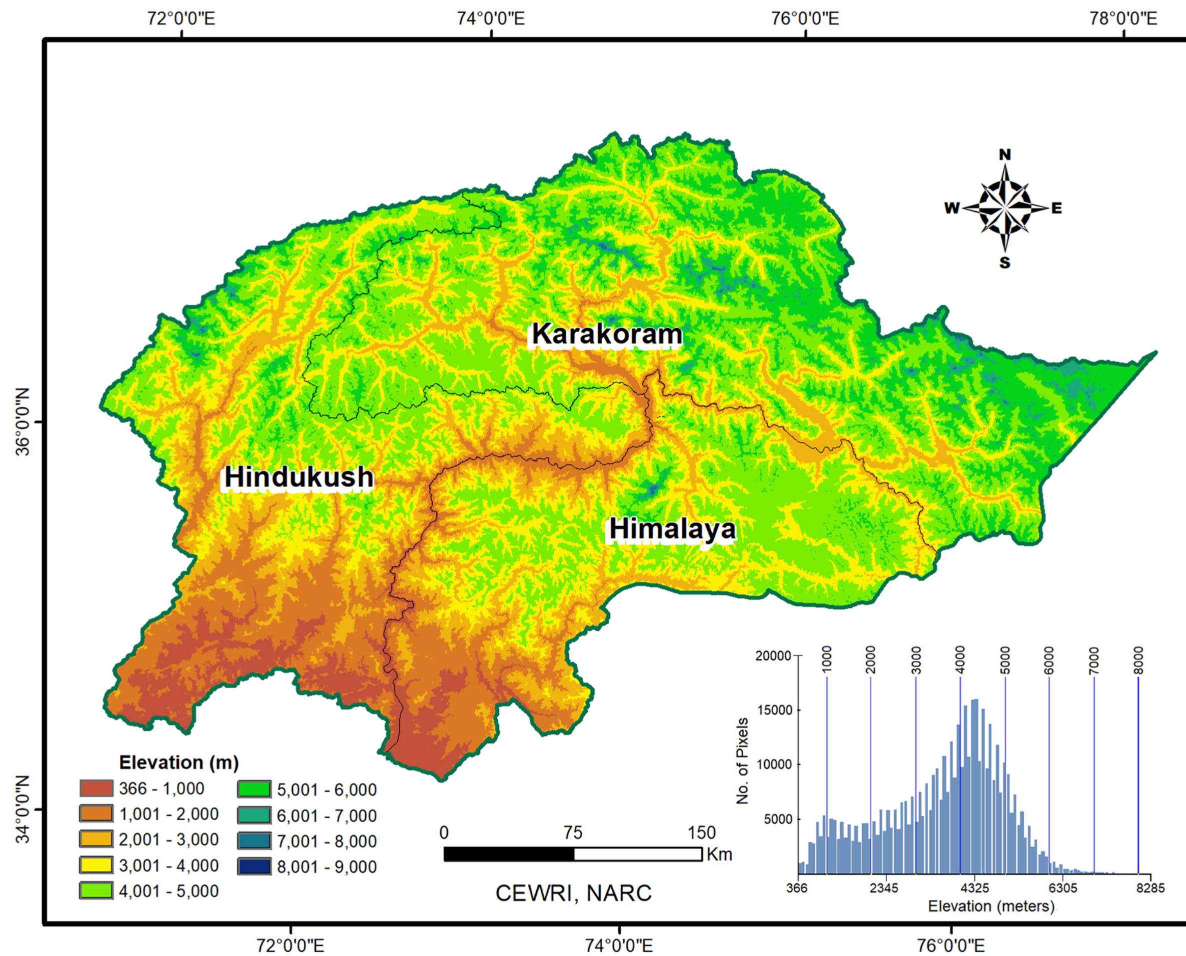

Fig. 2. Altitudinal variations in the three HKH ranges.

The climate is characterized by low rainfall and aridity. Annual rainfall ranges between 125 and 500 mm, which is usually received in summer from the monsoon and in winter from the westerlies. In addition to the global weather systems, the climate is also influenced by valley orientations, slope, aspect, and elevation at medium to local scale (Awan, 2002; Zurick et al., 2006). Springs are not extensive – their discharge is available under localized conditions (NASSD, 2001), therefore about 65.8% of the total irrigated area in Gilgit-Baltistan is fed by snow and glacial resource (GoGB, 2013), most commonly through kuhl system. The middle and higher reaches of the valleys (e.g. elevation ranging from 1900 to 2300 m, usually with dispersed settlements), is a marginal single cropping zone, that may be converted into double cropping zone with early maturing. High elevated valleys within 2300–3000 m elevation constitute single cropping zone, while >3000 m elevation comprises of mainly alpine pastures (NASSD, 2002). In single cropping zone, the main crops are wheat, barley, maize, potato and peas. There are >20 villages containing kuhl irrigation system in Gilgit sub-basin including Gulmuti, Gich, Bubar, Danyor, Shir Qillah and Forfoh, where the kuhl discharge ranges between 0.02 and 0.85 m^3/s (mean about 0.2 m^3/s). Mean cultivable command area (area under kuhl irrigation) per village is about 202 ha and average irrigation about 1.12 l/s/ha (WAPDA, 1988). In Hunza sub-basin, kuhl irrigation system is being practiced in >24 villages (e.g. Hoper, Miacher, Nagar, Chalt and Gulmit), where average discharge of kuhl varies within 0.2–1.42 m^3/s range (mean about 0.25 m^3/s). Mean cultivable command area per village is about 214 ha and average irrigation about 1.34 l/s/ha (WAPDA, 1988). The land holding size generally varies between 0.4 and 1.2 ha per house hold. Irrigation for wheat crop is usually applied at 7–12 days interval from land preparation and sowing in April and May, till the time of harvesting in August and September (Clemens and Nüsser, 2000).

3. Establishing a Kuhl irrigation system

The upper ends of kuhls are usually connected to perennial water source, i.e., streams originating from high altitude snow and glacial catchments; from clusters of small or medium glaciers or from a single large glacier (Fig. 3). The construction of kuhl over steep slopes is usually challenging, but fruitful in bringing nearby unused land under cultivation (Fig. 4). If the river has a steep gradient, water is diverted into a kuhl some distance upstream and led along the hill gradient so that it can flow under gravity to cultivated fields in the downstream. The kuhl irrigation system is mainly established over river terraces, alluvial fans and cone-shaped scree slopes. Over alluvial fans and scree slopes, the upper portions are usually cultivated first to stabilize slopes with trees and fodder crops (Fig. 5). Irrigation and labour-intensive construction, maintenance, and restoration of kuhls are generally conducted by community institutions (jirgas). At the time of construction of new irrigation channels, jirga recalculates and allots

Fig. 3. Kuhls are commonly established over snow and glacial fed streams for water supply in the Himalayan mountain region (Shigar basin: surveyed in 2017).

water rights based on the community's share of land (Bilal et al., 2003). This demonstrates the adaptive response of community institutions to socio-hydrological changes (Nüsser and Schmidt, 2016).

4. Materials and methods

The source data of glaciers was acquired from the last inventory developed by ICIMOD (2011) for Indus basin. The glacial

Fig. 4. Establishing kuhls over steep slopes to intake water from a glacier is common in the HKH mountain environment (Hunza basin, surveyed in 2017).

Fig. 5. Initial stage of cultivation area development through kuhl system (Hunza basin: surveyed in 2015).

parameters were determined using analytical techniques of GIS. Overall, 7392 glaciers (ice reserves of about 2111.89 km^3) were estimated in the three HKH ranges, out of which 23% lie in the Hindu Kush, 54.6% in the Karakoram and 22.4% in the Himalaya range, possessing ice reserves of about 9.1%, 88.9% and 2% respectively. The glacial potential for kuhl irrigation system was assessed through developing accessibility and yield indices of the glaciers (Table 1 and Table 2). The accessibility index is based on the minimum elevation of a glacier, i.e., high weight was assigned to glaciers having lower elevation <3500 m for easy access for establishing irrigation system. The elevations above 4500 m are usually difficult to establish channels for water supply, so low weight was assigned to the glaciers residing there. The yield index was developed using glacier size categories as defined by Muller et al. (1977), for simple basin. The glaciers having >10 km^2 area (i.e., containing substantial ice reserves for yielding water for irrigation) were assigned maximum weight of 4, while glaciers of <1 km^2 size were assigned a least weight of 1. According to glacier inventory by ICIMOD (2011), an average glacier size in Indus basin is about 1.14 km^2 and average ice reserve of a glacier is about 0.14 km^3. Finally, suitability index was developed, based on glacier accessibility and yield indices. The weights of two indices were multiplied and categorized into four classes, which were ranked according to the resource potential of glaciers for establishing kuhl irrigation (Table 3). Each index was assessed considering glacier number and ice reserves as potential resource in the three Himalayan ranges. Glacier numbers are important for identifying multiple connectivity sources, while ice reserves are important in term of assessing resource potential for developing kuhl system at varying scales in the region. The extent and distribution of the three indices, i.e., accessibility, yield and suitability were mapped for spatial analysis using ArcGIS software. Ground information were collected through field surveys and discussions with community members of the villages, e.g. Gilgit, Hunza, Skardu and Astore during 2013, 2015

Table 1
Glacier accessibility index based on minimum elevation of the glaciers.

Minimum elevation (m)	Weight	Accessibility
<3500	4	High
3500–4000	3	Medium
4000–4500	2	Average
>4500	1	Low

Table 2
Glacier yield index based on areal categories of the glaciers.

Glacier area (km^2)	Weight	Glacier yield
>10	4	High
5–10	3	Medium
1–5	2	Average
<1	1	Low

Table 3
Suitability index based on integration of accessibility and yield indices.

Suitability	Weight multiply	Rank
Good	>10	1
Fair	5–10	2
Medium	2–5	3
Low	<2	4

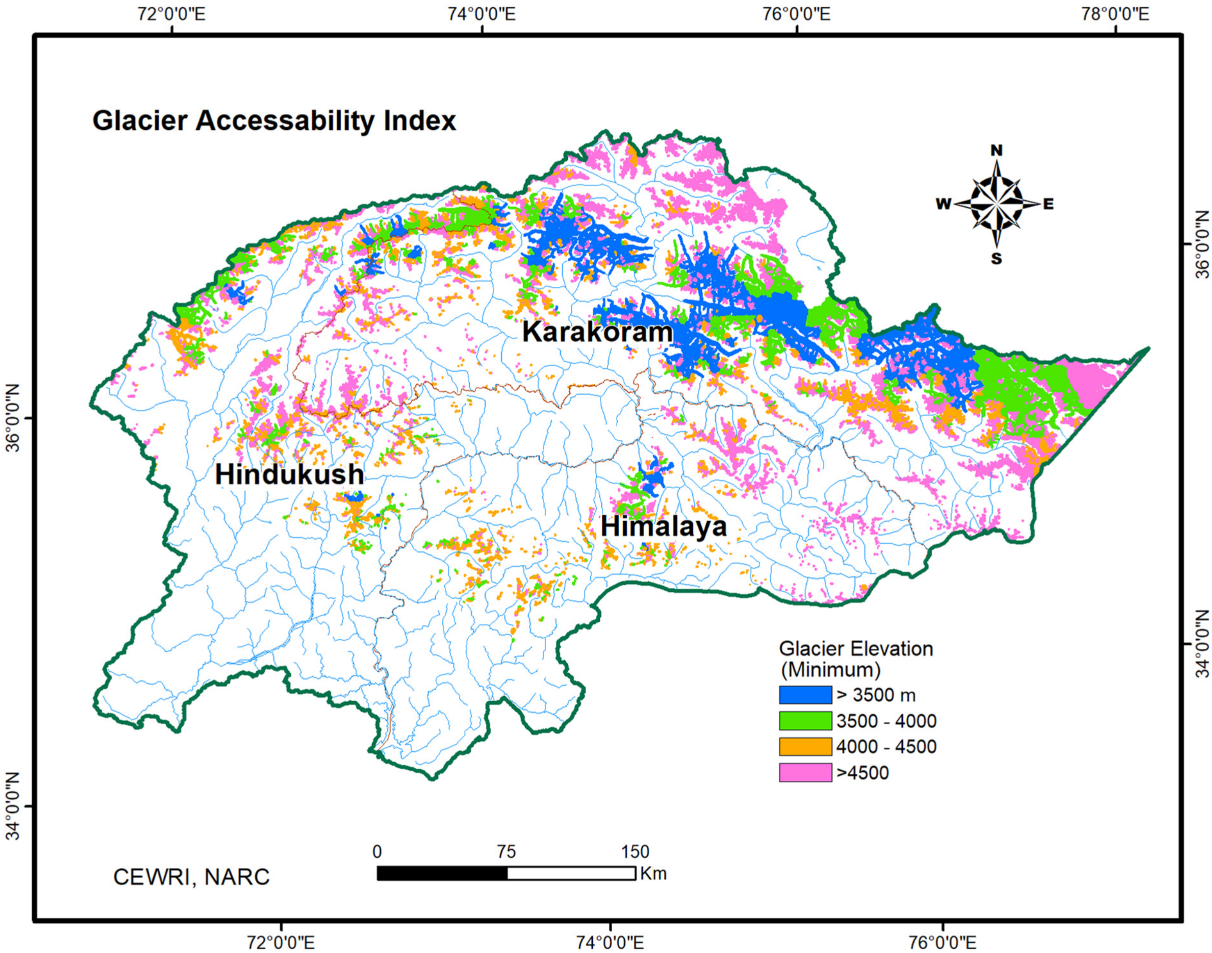

Fig. 6. Accessibility index based on minimum elevation of glacier in the HKH ranges.

and 2017. A correlation analysis of glaciers was performed with climate data of 1960–2010 period averaged over 10 sub-basins in the study area.

5. Results and discussion

5.1. Accessibility and yield of glacial resource

The accessibility index based on minimum elevation of glaciers indicated variable distribution of glaciers in the three HKH ranges (Fig. 6). Overall accessibility index was found high (minimum elevation <3500 m) for 1% glaciers (72) constituting 43.4% ice reserves of the HKH region (Table 4). Medium accessibility glaciers (elevation within 3500–4000 m) were 320 in numbers containing about 811.42 km^3 ice reserves of the region. Average accessibility (4000–4500 m elevation) was dominant in about 27% glaciers (1999) constituting 7% ice reserves, while 67.7% glaciers (5001) belong to low accessibility index (>4500 m elevation), constituting about 11.2% ice reserves only. In the Hindu Kush, accessibility index was high for 0.7% glaciers only (ice reserves about 9.4%). In the Karakoram, accessibility index was high for 1.3% glaciers only (cumulative ice reserves about 47.3%). Medium accessibility glaciers were 102 in numbers containing about 686.37 km^3 ice reserves. Average accessibility was dominant in about 16.5% glaciers (ice

Table 4
Glacier categorized by accessibility in the three HKH ranges.

Range	Hindu Kush		Karakoram		Himalaya		All ranges	
Minimum elevation (m)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)
<3500	12	18.040	53	889.140	7	9.026	72	916.206
3500–4000	135	113.016	102	686.375	83	12.025	320	811.416
4000–4500	622	44.524	667	90.931	710	11.896	1999	147.351
>4500	932	15.943	3215	211.460	854	9.516	5001	236.919
Total	1701	191.523	4037	1877.906	1654	42.463	7392	2111.892

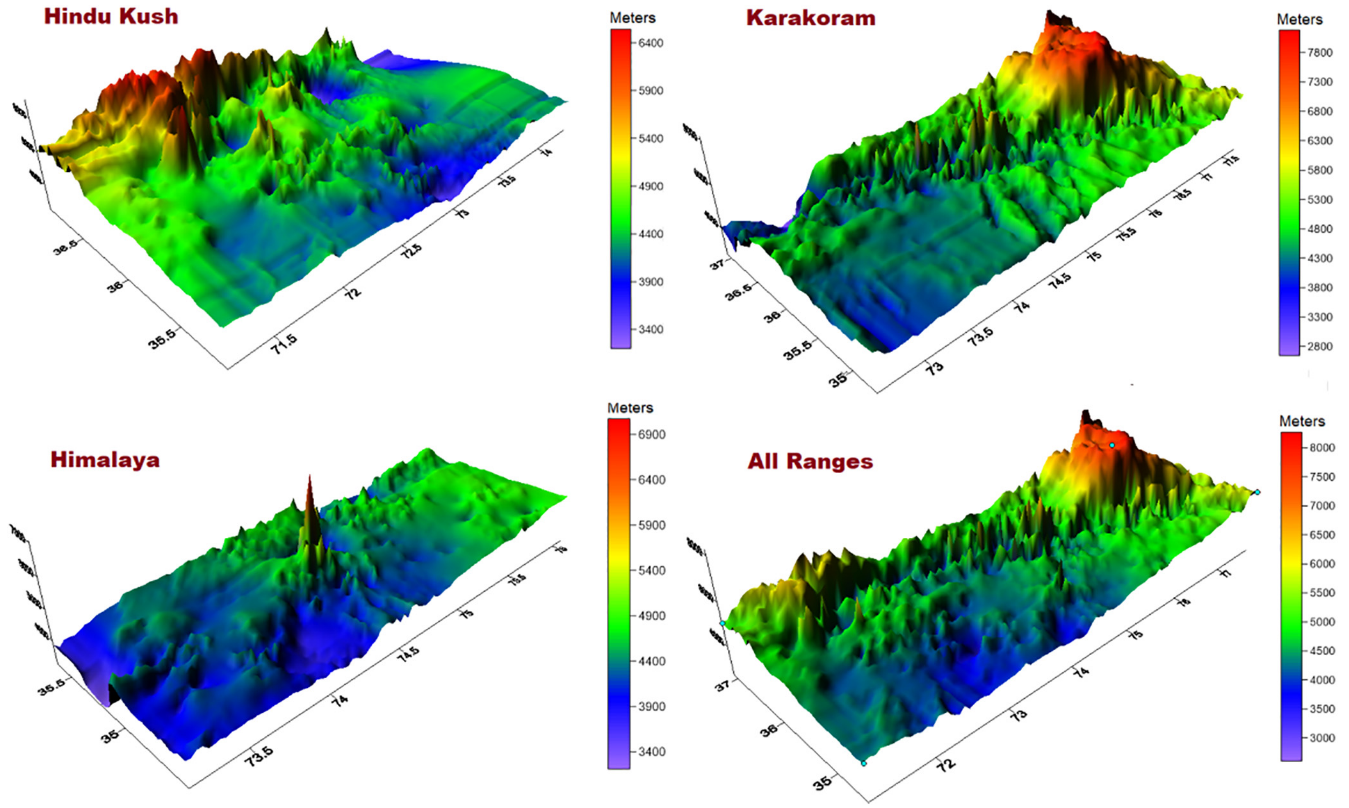

Fig. 7. Spatial trend of glacier elevation (minimum) in the HKH ranges.

reserves about 4.8%), while low accessibility was found for 79.6% glaciers (ice reserves about 11.3%). In the Himalayas, accessibility was high in about 0.4% glaciers constituting 21.3% of the range ice reserves (Table 4). Medium accessibility was found in 83 glaciers with cumulative ice reserves of about 12.02 km^3, while average and low accessibilities were dominant in 710 and 854 glaciers containing ice reserves of about 11.89 km^3 and 9.52 km^3, respectively. Although spatial trends of glacial elevation is variable in the three ranges, but mostly incline towards southeast, east and southwest directions (Fig. 7).

The glacier yield index was high (>10 km^2 areal category) for 1.6% glaciers constituting 89% of the total ice reserves of HKH region, while low yield index (<1 km^2 areal category) exhibited 83.3% glaciers with 2.2% ice reserves only (Table 5). Medium yield index (5–10 km^2 category) was dominant in 133 glaciers with cumulative ice reserves of about 74.22 km^3, while average yield was found in 983 glaciers containing ice reserves of over 112.53 km^3 (Table 5 and Fig. 8). In the Hindu Kush, The glacier yield index was high for 1.6% glaciers constituting 73.8% of the total ice reserves of the range, while low yield index (<1 km^2 category) exhibited 85.2% glaciers with 5.6% ice reserves only (Table 5). The former category contains a giant glacier - *Chiantar* lying in the northeast of Chitral basin. Medium yield index was dominant in 30 glaciers with cumulative ice reserves of about 17.53 km^3, while the yield was average for 195 glaciers containing ice reserves of over 21.97 km^3. About 2.2% of the total Karakoram glaciers belong to >10 km^2 category (e.g. the renowned ones are *Baltoro, Biafo, Panmah, Chogo Lungma, Siachen, Batura and Hispar*), majority of which lie in Hunza basin. Presence of large sized glaciers in the Karakoram points towards stable climatic conditions conducive for glacial formation in this range – the fact exclusively highlighted by various researchers (e.g. Gardelle et al., 2013; Hewitt, 2005; Kääb et al., 2012). Medium yield index was dominant in 94 glaciers with cumulative ice reserves of about 51.74 km^3, while the yield was average for 648 glaciers containing ice reserves of over 76.22 km^3. The glaciers with <1 km^2 area were 79.4% in numbers constituting 1.4% ice reserves

Table 5
Glaciers categorized by surface area in the HKH ranges.

Range	Hindu Kush		Karakoram		Himalaya		All ranges	
Glacier area (km^2)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)
>10	27	141.285	88	1723.459	6	13.999	121	1878.742
5–10	30	17.529	94	51.744	9	4.952	133	74.224
1–5	195	21.974	648	76.228	140	14.334	983	112.537
<1	1449	10.735	3207	26.475	1499	9.179	6155	46.389
Total	1701	191.521	4037	1877.904	1654	42.464	7392	2111.889

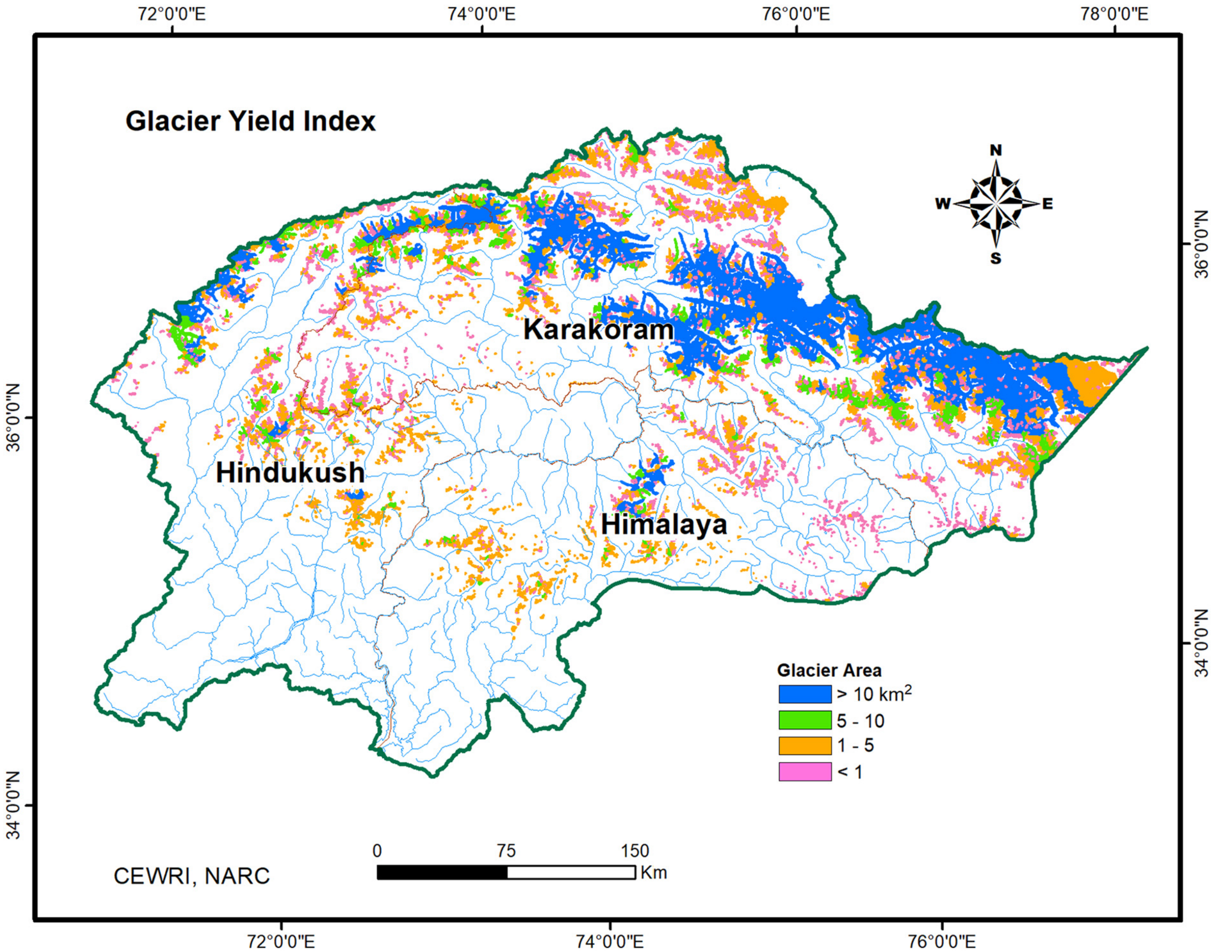

Fig. 8. Yield index based on areal categories of the glaciers in the HKH ranges.

only. In the Himalayas, glacier yield index was high for 0.4% glaciers constituting 33% ice reserves of the range, while low yield index exhibited 90% glaciers with 21.6% ice reserves. Medium yield index was dominant in 9 glaciers with cumulative ice reserves of about 4.95 km^3, while the yield was average for 140 glaciers containing ice reserves of over 14.33 km^3.

5.2. Glacial resource potential

The glacial suitability was mapped exhibiting distribution of glacial potential in the three HKH ranges (Fig. 9). Suitability index was found good for about 1.4% glaciers of the HKH region constituting about 80% ice reserves, while it was low for 60% glaciers constituting about 1.5% of the total ice reserves only (Table 6 and Fig. 10). Fair suitability was found in 200 glaciers with ice reserves of about 125.11 km^3 and medium suitability in 2669 glaciers with ice reserves of about 267.15 km^3. In the Hindu Kush, suitability was good for about 1.4% glaciers (ice reserves about 64.1% of the range), while it was low for about 49.7% glaciers (ice reserves about 3.1%). Fair and medium potential comprises of 54 and 778 glaciers containing ice reserves of about 36.38 km^3 and 26.42 km^3, respectively (Table 6). In the Karakoram, suitability was good for 1.7% glaciers containing ice reserves of about 82.9%, while fair potential comprised of 3% glaciers containing about 4.2% of the range ice reserves. Medium potential comprised of 1073 glaciers (ice reserves about 220.58 km^3), while it was low for 68.7% glaciers (ice reserves about 1.2% only). In the Himalayas, suitability was good for about 0.5% glaciers containing ice reserves of about 18.7%, while fair potential comprised of 1.5% glaciers containing about 21.4% of the total range ice reserves. Medium potential comprised of 818 glaciers containing ice reserves of over 20.15 km^3 (Table 6). Suitability was low for 48.5% glaciers constituting 12.4% ice reserves of the range.

Suitability index was estimated river basin wise in order to assess irrigation potential and resource planning on micro level. In the Hindu Kush basins, suitability was good for 22 and fair in 38 glaciers of the Chitral basin (Table 7). Medium suitability was dominant in 334 glaciers in the Indus part and 248 glaciers in the Chitral basin. In Swat, medium suitability was about 60% by number and 74% by reserve of the glaciers. Low suitability was found for 615 glaciers in Chitral followed by 126 glaciers in Swat basin. In the Karakoram basins, suitability was good for 16, 28, 12 and 9 glaciers and fair for 43, 22, 28 and 23 glaciers of the Gilgit, Hunza, Shigar and Shyok basins, respectively (Table 8). The glacial melt is accessible due to descending of several large valley type glaciers lying at lower elevations, i.e., below 3500 m in these basins, e.g. ice melt from Ghulkin glacier (a valley type glacier having 22.1 km^2 area and snout at about 2694 m elevation) is supplied through kuhl-pipe system for irrigation and domestic use to nearby Hussaini village (Fig. 11). Medium suitability was prominent in 357 glaciers in Hunza and 348 glaciers in Gilgit basin, while in Shigar and Shyok basins, it was about 28.4% and 18.2% by number, and 1.7% and 20.2% by glacial reserve, respectively. Low suitability was found for 974 glaciers in Hunza and 833 glaciers in Shyok

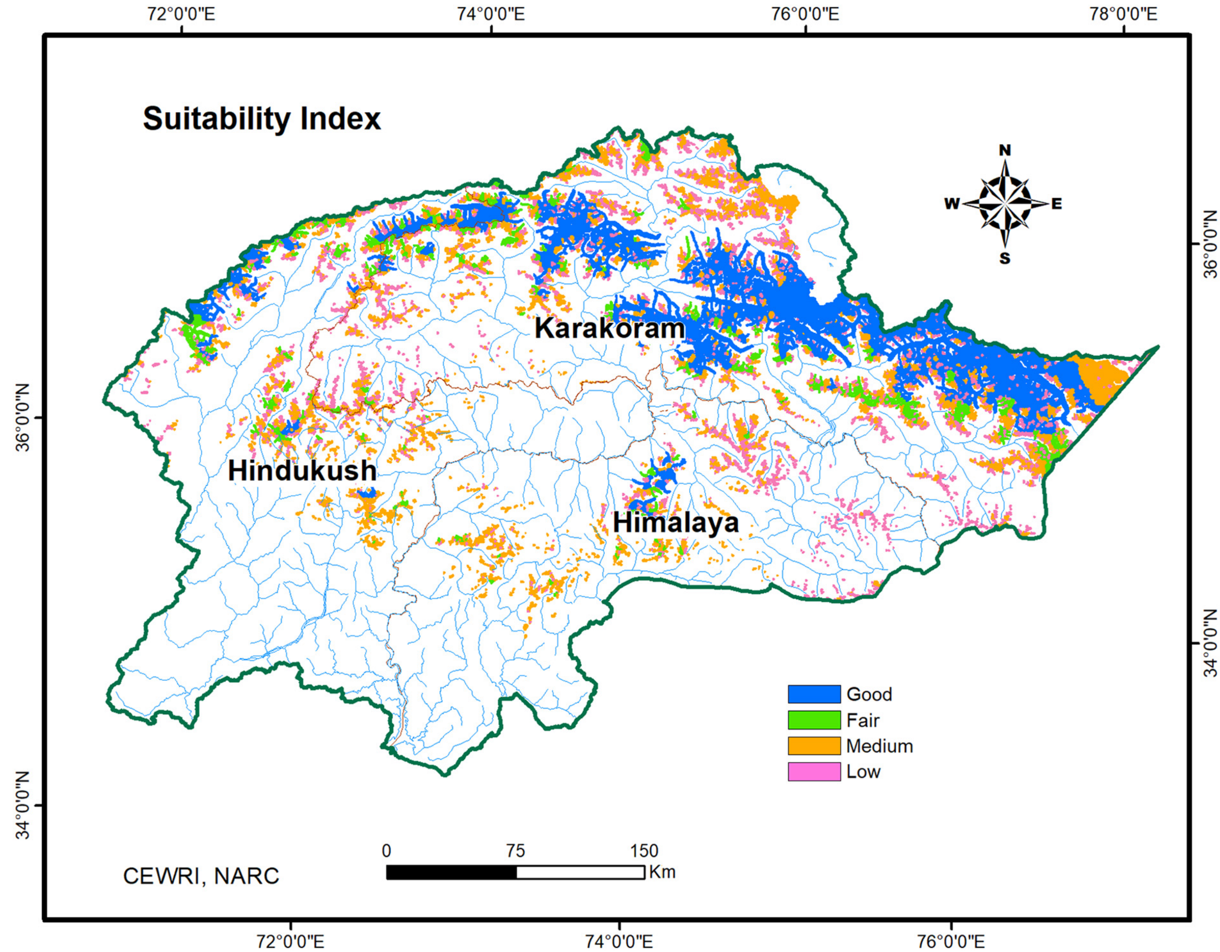

Fig. 9. Suitability index indicating resource potential of glaciers in the HKH ranges.

basin. In the Himalayas, suitability index was good for 5, 1 and 3 glaciers of Astore, Jhelum and Indus part of the Himalaya, respectively (Table 9). According to Farhan et al. (2015a, 2015b), >70% of the Astore river flows are fed by the melts of snow and glaciers. The kuhl-pipe system is usually followed to supply water across roads/river/streams (Fig. 12). In Tarishing town of Astore, the irrigation as wells domestic water requirements are mostly met by kuhl system fed by a nearby Chungphare glacier (Fig. 13), a valley type glacier (area about 19.2 km^2 and ice reserves about 2.259 km^3), which descends from about 6757 m down to 2991 m elevation (ICIMOD, 2011). Medium suitability was dominant in 363 glaciers in the Indus part and 284 glaciers in the Jhelum basin, while low suitability was prominent in 325 glaciers in the Indus part and 205 glaciers in the Shingo basin.

Unit glacial reserve (UGR) was estimated for different suitability indices to conceive unit glacial potential in different river basins (Tables 7–9). For good suitability, UGR was high for Shyok basin, i.e., 59.46 km^3 followed by Shigar basin, i.e., 49.54 km^3, while for fair suitability, it was high for Astore (1.5 km^3) and Shyok basin (1.4 km^3). On an average, UGR was maximum for Shigar basin, i.e., 1.44 km^3, and among HKH ranges, for the Karakoram range, i.e., 0.46 km^3.

The kuhl irrigation system is highly vulnerable to extreme events of climate change like flash floods, landsliding and GLOFs. According to

Table 6
Suitability of glacial resource potential in the HKH ranges.

Range	Hindu Kush		Karakoram		Himalaya		All ranges	
Potential	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)	Number	Ice reserves (km^3)
Good	24	122.777	70	1556.069	9	7.961	103	1686.807
Fair	54	36.381	121	79.658	25	9.076	200	125.115
Medium	778	26.416	1073	220.58	818	20.153	2669	267.149
Low	845	5.947	2773	21.597	802	5.274	4420	32.818
Total	1701	191.521	4037	1877.904	1654	42.464	7392	2111.889

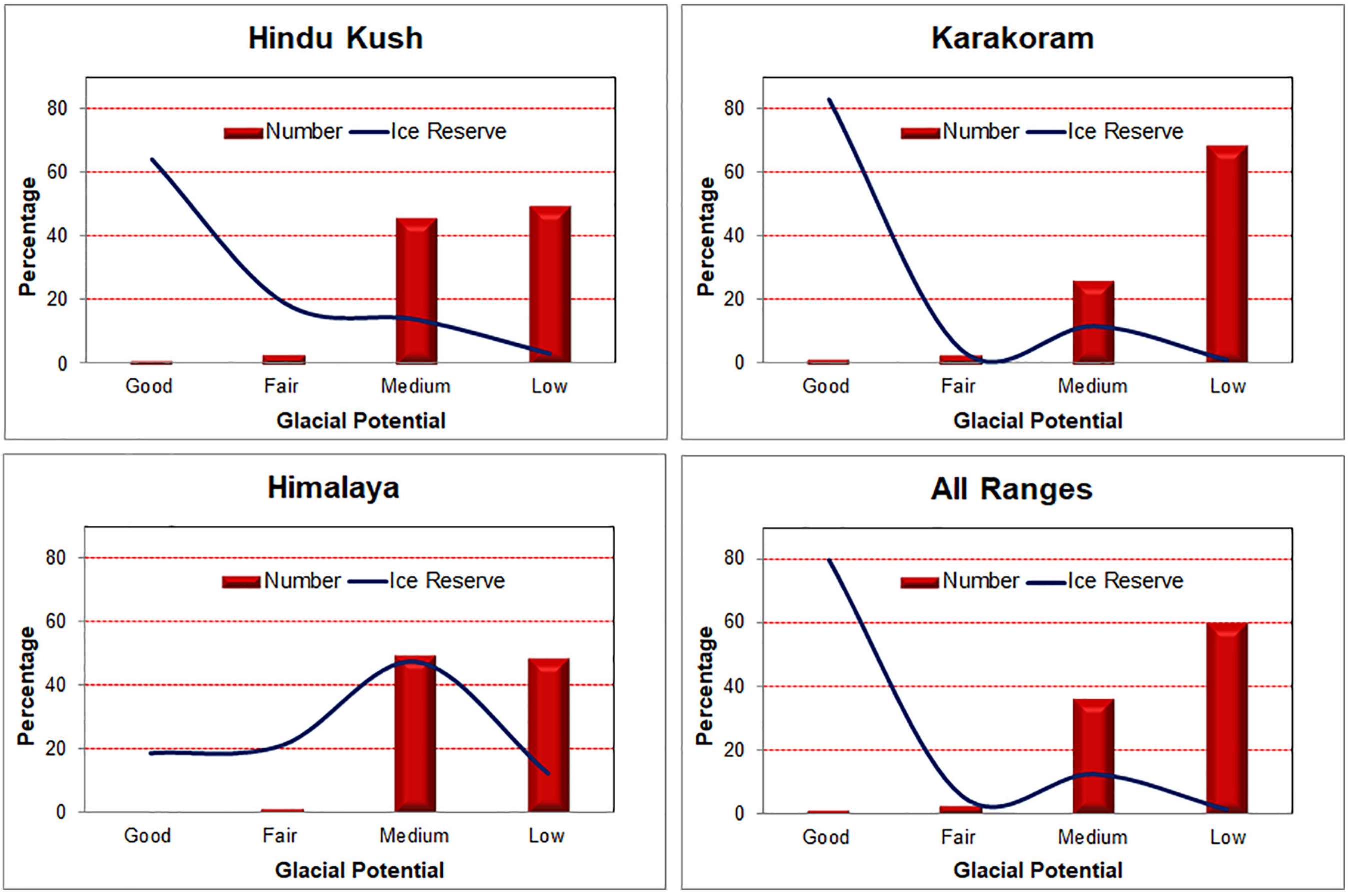

Fig. 10. Suitability index of glaciers by percentage number and ice reserve of glaciers in the HKH ranges.

Farooqi et al. (2005), there is a gradual increase in temperatures as well as precipitation observed over the last few decades in this region. During 2010 and 2011, the intense rainfall events in the Gilgit-Baltistan province triggered many glacial lakes resulting in heavy damages to the infrastructure and agricultural land (Ashraf et al., 2015, 2017). In order to reduce vulnerability to climate induced hazards, e.g. glacial floods, landslides, and to minimize the maintenance cost, pipe flow irrigation system can be encouraged to use rather than open channels under participatory development approaches. Skilled manpower and local experience are thus essential in identifying suitable sites, viable design, proper construction and maintenance of the kuhl system. The financial needs can be efficiently met through public-private partnership. In Ishkuman valley of Gilgit basin, local community was engaged in development of 1.2 km long kuhl through public funding of about 0.7 million rupees, that had positively influenced their livelihood and added relief to their lives.

Table 7
Suitability of glacial resource potential in the Hindu Kush basins.

Basin	Potential	Number	Ice reserve	% Number	% Reserve	Unit glacial reserve
Swat	Good	0	0	0.0	0.0	–
	Fair	5	0.739	1.5	13.6	0.148
	Medium	196	4.041	59.9	74.1	0.021
	Low	126	0.672	38.5	12.3	0.005
Sub-total		327	5.452	100.0	100.0	0.017
Chitral	Good	22	120.315	2.4	67.8	5.469
	Fair	38	34.255	4.1	19.3	0.901
	Medium	248	18.219	26.9	10.3	0.073
	Low	615	4.716	66.6	2.7	0.008
Sub-total		923	177.505	100.0	100.0	0.192
Indus part	Good	2	2.462	0.4	28.7	1.231
	Fair	11	1.387	2.4	16.2	0.126
	Medium	334	4.156	74.1	48.5	0.012
	Low	104	0.559	23.1	6.5	0.005
Sub-total		451	8.564	100.0	100.0	0.019
Total		1701	191.521			0.113

Table 8
Suitability of glacial resource potential in the Karakoram basins.

Basin	Potential	Number	Ice reserve	% Number	% Reserve	Unit glacial reserve
Gilgit	Good	16	36.936	1.7	50.0	2.309
	Fair	43	14.915	4.4	20.2	0.347
	Medium	348	17.806	36.0	24.1	0.051
	Low	560	4.24	57.9	5.7	0.008
Sub-total		967	73.897	100.0	100.0	0.076
Hunza	Good	28	372.873	2.0	85.7	13.317
	Fair	22	9.781	1.6	2.2	0.445
	Medium	357	44.419	25.9	10.2	0.124
	Low	974	8.165	70.5	1.9	0.008
Sub-total		1381	435.238	100.0	100.0	0.315
Shigar	Good	12	594.494	2.7	94.3	49.541
	Fair	28	21.89	6.4	3.5	0.782
	Medium	124	10.984	28.4	1.7	0.089
	Low	273	2.748	62.5	0.4	0.010
Sub-total		437	630.116	100.0	100.0	1.442
Shyok	Good	9	535.143	0.9	74.5	59.460
	Fair	23	32.215	2.2	4.5	1.401
	Medium	192	145.019	18.2	20.2	0.755
	Low	833	5.839	78.8	0.8	0.007
Sub-total		1057	718.216	100.0	100.0	0.679
Indus	Good	5	16.623	2.6	81.3	3.325
	Fair	5	0.857	2.6	4.2	0.171
	Medium	52	2.352	26.7	11.5	0.045
	Low	133	0.605	68.2	3.0	0.005
Sub-total		195	20.437	100.0	100.0	0.105
Total		4037	1877.904			0.465

6. Conclusions

In this study, an indexing approach based on accessibility and water yield of the glacial resource was adopted to assess potential of the melt water resource for developing kuhl irrigation in the Himalayan ranges. Suitability index was found good for 1.4% glaciers constituting about 80% ice reserves of the HKH region, while it was low for 60% glaciers constituting about 1.5% ice reserves only. Fair suitability was found in 200 glaciers containing ice reserves of about 125.11 km^3 and medium in 2669 glaciers with ice reserves of about 267.15 km^3. Unit glacial reserve estimated for different suitability indices indicated maximum average value for Shigar

Fig. 11. In order to avoid impacts of glacial flooding, water is supplied through pipes for safe transmission in the region (Hunza basin, surveyed in 2017).

Table 9
Potential of glacial resource in the Himalaya basins.

Basin	Potential	Number	Ice reserve	% Number	% Reserve	Unit glacial reserve
Shingo	Good	0	0	0.0	0.0	–
	Fair	0	0	0.0	0.0	–
	Medium	6	0.004	2.8	0.3	0.001
	Low	205	1.273	97.2	99.7	0.006
Sub-total		211	1.277	100.0	100.0	0.006
Astor	Good	5	7.957	1.3	26.3	1.591
	Fair	6	9.016	1.6	29.8	1.503
	Medium	165	12.025	44.5	39.8	0.073
	Low	195	1.242	52.6	4.1	0.006
Sub-total		371	30.24	100.0	100.0	0.082
Jhelum	Good	1	0.003	0.3	0.1	0.003
	Fair	7	0.038	1.9	1.8	0.005
	Medium	284	1.789	77.0	84.8	0.006
	Low	77	0.28	20.9	13.3	0.004
Sub-total		369	2.11	100.0	100.0	0.006
Indus	Good	3	0.001	0.4	0.0	0.000
	Fair	12	0.022	3.3	0.2	0.002
	Medium	363	6.335	98.4	71.7	0.017
	Low	325	2.479	88.1	28.1	0.008
Sub-total		703	8.837	190.5	100.0	0.013
Total		1654	42.464			0.026

basin (i.e., 1.44 km^3) and among HKH ranges, for the Karakoram range (i.e. 0.46 km^3). Kuhl irrigation should be followed by farm pond storage for providing excess water for raising high value crops. Innovative and efficient irrigation systems (e.g. drip, sprinkler) can be adopted for alleviating poverty and improving livelihoods. A detail analysis of the hydrodynamics of glacial resource would prove effective in predicting future ice-melt and river flows for water management in this region in future.

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Fig. 12. Kuhls-pipe combination for supplying water across a perennial stream is not unusual in the region (Astore basin, surveyed in 2017).

Fig. 13. Kuhl fed by the melt of Chungphare glacier (>10 km^2 in size: Elevation <3500 m) supplies irrigation water to Tarishing valley (Astore basin: surveyed in 2017).

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